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LUMINARY Memo #213

TO: Distribution

FROM: C. Work

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SUBJECT: Guidance and Control Stability Tests of LUMINARY 1E; Part 2

REFERENCES: LUMINARY Memo #203, "Guidance and Control Stability Tests of LUMINARY 1E"

This memo documents the continuation of a test series. LUMINARY Memo #203 documents the first part of the test series, and it also explains the motivation for performing these tests. Part 2 of the test series is a collection of external delta-V burns (P40 and P42) executed with and executed without an erroneous AGS indication. The test situations are aggravated by extreme attitude transients (a 10° transient every 20 seconds, cycling through the X, Y, and Z desired IMU CDUs) or by extreme slosh transients (all slosh masses are placed in phase, all moved to a point .25 tank radii forward (+Z) of the tank c.g.).

Experience with the P63 (descent) Burns established that the descent LM configuration controls normally, with or without a false AGS indication, when the DPS fuel loading is greater than 35% or less than 17%. (See LUMINARY Memo #203). It was also evident that the least stable responses to slosh and attitude tweaks (with the descent configuration) were displayed at the end of a guidance phase (meeting end conditions) or at DPS fuel loadings about 30-35%. As a result, the P40 tests cover the range of DPS fuel loadings from 33% to 17%, with attitude tweaks throughout, or with a slosh tweak

immediately after throttle-up to full thrust, about 85 seconds before burn termination.

The P42 tests were run at APS fuel loadings of .9, .27, .127, the last case going to APS fuel depletion about 2-3 seconds before the end of a 60 second burn. The attitude tweaks were applied every 20 secs, while the slosh tweak was introduced at TIG + 3 sec. The three separate burns in P42 testing permitted examination of the system behavior under stress at the end of a burn, (when the guidance is meeting end conditions), for a representative span of loadings.

Test Results

The noun 85 readings generated at the end of the burns show the remaining delta-V to be achieved. 2.0 feet/sec of the N85 X component reflect the mismatch between the LUMINARY value for the DPS engine tailoff momentum and the environment value, in the P40 burns. Therefore, 2.0 feet/sec should be subtracted from the X component in assessing the effect of the slosh and attitude tweaks on the guidance accuracy. The P42 burns, in contrast to the P40 underburn, will show overburns of 0.1, 0.2, 0.2 feet/sec in the X components of the burns at 0.9, .27, .127 APS fuel load.

P40 Results

Attitude Response .33 DFUEL loading

AGS indication: RCS added to the slosh energy at each attitude tweak, but the cumulative total was essentially stable after FTP, as the RCS removed as much as it added. The GTS increased the slosh energy steadily, slowly at low thrust, more quickly after FTP, eventually reaching 60% of the RCS slosh energy input. The largest rate responses to the tweaks were 4.0, -6.5, -6.0 degrees per second in the P, Q, and R axes. Slosh mass displacement damped steadily throughout the burn. At burn termination, the V16 N85 readings were (+2.2, -0.5, +0.4) feet/sec.

PGNCS indication: PGNCS performance was essentially identical to the AGS case.

Slosh Response .33 DFUEL loading

AGS indication: The slosh tweak came three seconds after throttle-up to full thrust (FTP), and GTS pumped the slosh steadily, reaching a total 2.6 times the input energy of the attitude tweak case. The RCS slosh energy input total rose to about half the GTS maximum, but was reduced to 23 joules at engine cut-off. The RCS energy input maximum coincided with a 30 second period of cross-coupled oscillation in the P-axis, which generated no yaw firings. The largest rate responses were -.62, -3.3, 2.1 degrees per second in the P, Q, and R axes, respectively. RCS fuel consumption was about 60% of the consumption in the attitude tweak case, which reflects the absence of RCS firings to meet suddenly "tweaked" guidance requests. At burn termination, the slosh mass displacements were slowly damping, and the Noun 85 readings were (2.8, -1.2, 0.2).

PGNCS indication: GTS slosh energy input was about 60% of that in the AGS case, while the RCS removed energy at a tremendous rate. Slosh mass displacements damped throughout, rates and attitudes were well controlled, and the Noun 85 was (2.4, -0.5, 0.4).

P42 Results

Attitude Response

AGS indication: .127 AFUEL loading

Control settled nicely between attitude tweaks, and the rates were larger than the P40 rates, which is one predictable difference between the ascent and the descent configuration performances. The APS engine slosh energy input total was negligible, and the RCS input total came to 46 joules, leveling off between attitude tweaks. Slosh mass displacements were damping when the APS fuel was exhausted, 2 or 3 seconds before the nominal termination of the burn.

PGNCS indication: .127 AFUEL loading.

The PGNCS burn closely resembled the APS burn, in all respects.

AGS indication: .27 AFUEL loading.

Slosh mass displacements were essentially unchanged after the tweak, and the total slosh energy input from the APS and the RCS was about 60% of the input seen in the burn at .127 loading with false AGS indication. Otherwise the two burns were largely similar. The terminal Noun 85 for this burn showed large cross-axis velocity errors. Those were caused by the last Z-axis attitude "tweak", as shown below.

The "tweak" mechanism was implemented by adding 10 degrees to the desired CDUZ reading, then the following FINDCDUW pass was skipped, allowing the DAP time to move the vehicle through the 10 degrees. After that, the guidance was to shift the desired CDUZ back to the correct heading. In this run, after the 10 degree tweak and the skipped FINDCDUW pass, the guidance saw less than 4 seconds of burn time remained, so no more corrections were issued to the desired CDU values. Therefore, the DAP averaged a 10 degree disagreement with Noun 22 in the final 3 seconds of the burn, generating the observed delta-V errors.

PGNCS indication: .27 AFUEL loading

The slosh mass displacements in the Y and Z axes were about equal and were damping at engine off. Otherwise, this run resembles the burn with AGS indication.

AGS indication: .9 AFUEL loading

Slosh mass displacement reached its maximum in both Y and Z axes at engine-off, but was still small. Both APS and RCS pumped the slosh energy, but the total was only 60 joules. The Q axis angular rate reached 10 deg/sec in responding to the Q attitude tweak, but this transient quickly settled back to normal ascent configuration burn rates.

PGNCS indication: .9 AFUEL loading

The PGNCS run and the AGS run showed no meaningful differences.

Slosh Response

AGS indication: .127 AFUEL loading

Slosh mass displacements consistently reached amplitudes of .25 to .30 tank radii, with ±Z motions at the beginning of the run and with ±Y motions dominating in the latter half of the burn. Control was normal, with 100 joules of slosh energy input by the control process. Fuel was exhausted 2-3 seconds before nominal termination of the burn.

PGNCS indication: .127 AFUEL loading

Slosh mass displacements slowly damped throughout the run, and total slosh energy input by the control was 19 joules. Fuel exhaustion terminated the burn 2-3 seconds early.

AGS indication: .27 AFUEL loading

Slosh mass displacements damped steadily, being reduced by a factor of 3 in 55 seconds. Slosh energy was extracted from the slosh mode by the control, coming to -77 joules. Relatively large P-axis rates were seen during a strong oscillation, cross-coupled from the Q, R axes about 30 sec after the slosh tweak. Noun 85 was (0.6, -0.1, 0.6).

PGNCS indication: .27 AFUEL loading

This run was similar to the AGS run in all respects.

AGS indication: .9 AFUEL loading

Slosh mass displacements damped almost completely, then grew slightly, remaining small at the end of the burn. Cross-coupled P-axis oscillations produced relatively large yaw rates, but these lasted only about 30 seconds. Control system removed energy from the slosh mode, and the Noun 85 was (0.5, 0, -0.8).

PGNCS indication: .9 AFUEL loading

Slosh mass damping was slower than in the AGS case, but otherwise the two cases were similar. Noun 85 was (-0.2, -0.2, 0).

Summary

LUMINARY 209 operates successfully in external delta-V burns (P40 and P42) with an erroneous AGS indication. All runs showed no guidance oscillations in response to attitude tweaks or to slosh tweaks. In all cases, the burn was executed satisfactorily with or without a false AGS indication and in the presence of extreme slosh and attitude transients.

	V16 N85	RCS fuel	engine slosh energy at cutoff	RCS slosh energy at cutoff	slosh mass displacement at cutoff	Max rate response to tweaks deg/sec		
	X Y ft/sec Z	lbm	joules	joules	tank radii	P	Q	R
P40, Att. Tw, .33 Dfuel, PGNCS	+ 2.2 - 0.6 + 0.4	33.8	63	110	.06	4.0	- 6.5	-6.0
AGS	+ 2.2 - 0.5 + 0.4	34.7	62	105	.04	4.0	- 6.5	-6.0
P42, Att. Tw, .127 Afuel*, PGNCS	+45.2 + 0.1 + 0.2	14.6	3.8	51	.11	5.1	+ 8.3	+7.5
* AGS	+45.4 + 0.3 + 0.7	14.4	4.0	46	.02	5.0	- 8.0	-8.2
.27 Afuel, PGNCS	- 1.2 - 7.6 + 3.3	11.9	1.9	28	.03	5.8	- 7.7	8.0
AGS	- 0.5 - 6.9 + 2.7	11.9	6.8	25	.03	6.5	- 7.8	7.8
.9 Afuel, PGNCS	0.1 - 0.4 - 0.6	17.5	26	31	.08	6.0	+10.0	6.6
AGS	0.2 - 0.4 - 0.9	17.4	20	40	.09	5.8	10.0	-6.7
P40, Slosh tw, .33 Dfuel, PGNCS	+ 2.4 - 0.5 + 0.4	18.1	128	-278	.09	.04	-4.0	1.8

Continued

Continued		V16 N85 X Y ft/sec Z	RCS fuel lbm	engine slosh energy at cutoff joules	RCS slosh energy at cutoff joules	slosh mass displacement at cutoff tank radii	Max rate response to tweaks deg/sec P	Q	R
	AGS	+ 2.8 - 1.2 + 0.2	20.9	162	23	.10	-.62	-3.3	2.1
P42, Slosh tw, .127 Afuel*,	PGNCS	+43.9 + 0.5 + 2.7	13.5	1.3	17	.18	.77	-4.2	4.9
*	AGS	+45.3 - 0.6 + 0.2	13.5	5.8	98	.41	.36	-3.9	-7.0
.27 Afuel,	PGNCS	+ 0.4 + 0.3 - 0.2	10.2	-61	-9.1	.09	-1.5	-2.9	-3.8
	AGS	+ 0.6 - 0.1 + 0.6	10.5	-49	-28	.06	1.5	-3.2	3.2
.9 Afuel,	PGNCS	- 0.2 - 0.2 0	16.1	21	-72	.11	3.0	6.5	3.2
	AGS	+ 0.5 + 0 - 0.8	16.8	18	-94	.05	-2.8	6.5	-3.4

* Fuel exhausted before ΔV requirements were met.